Advances in Understanding Earth's Energy Budget

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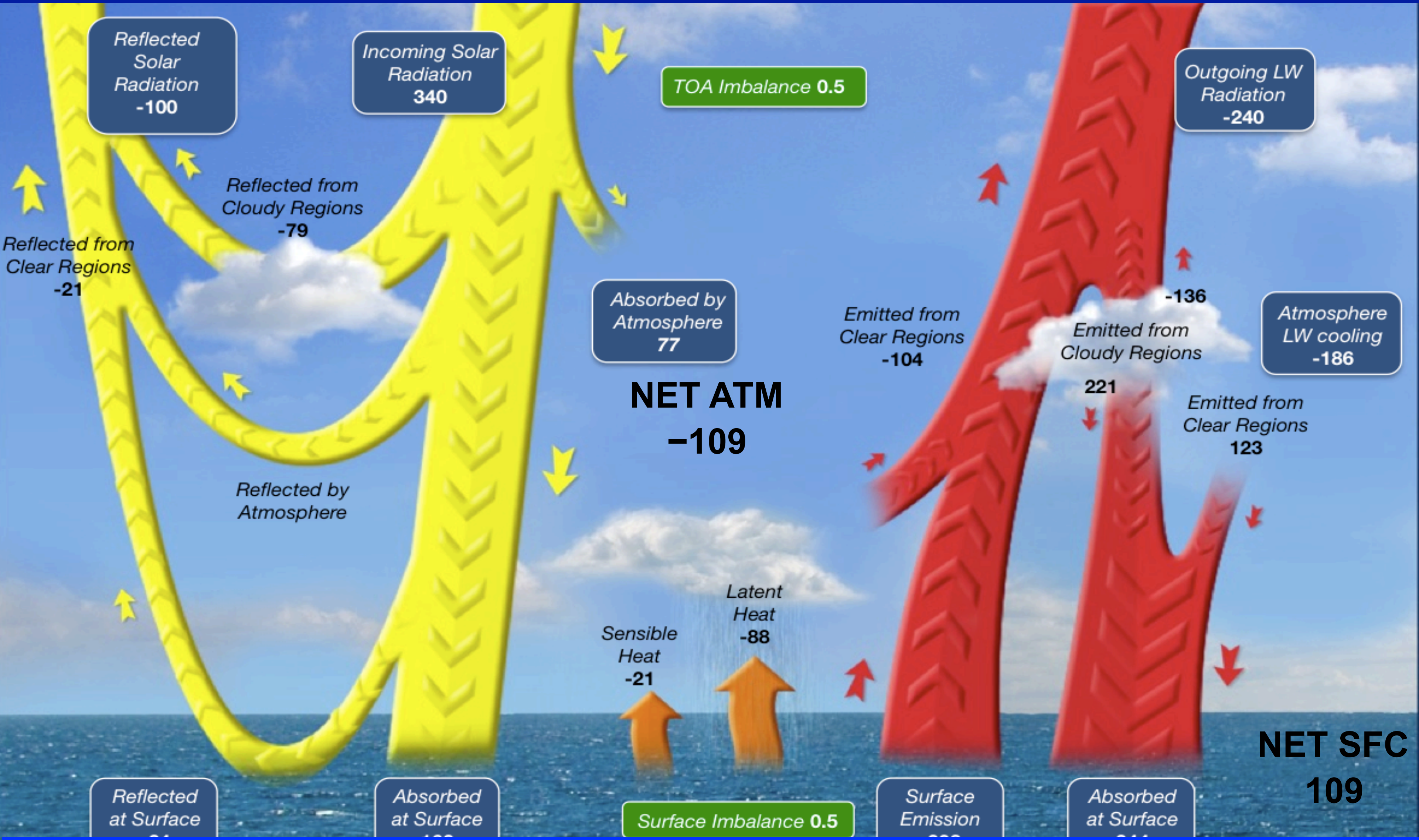
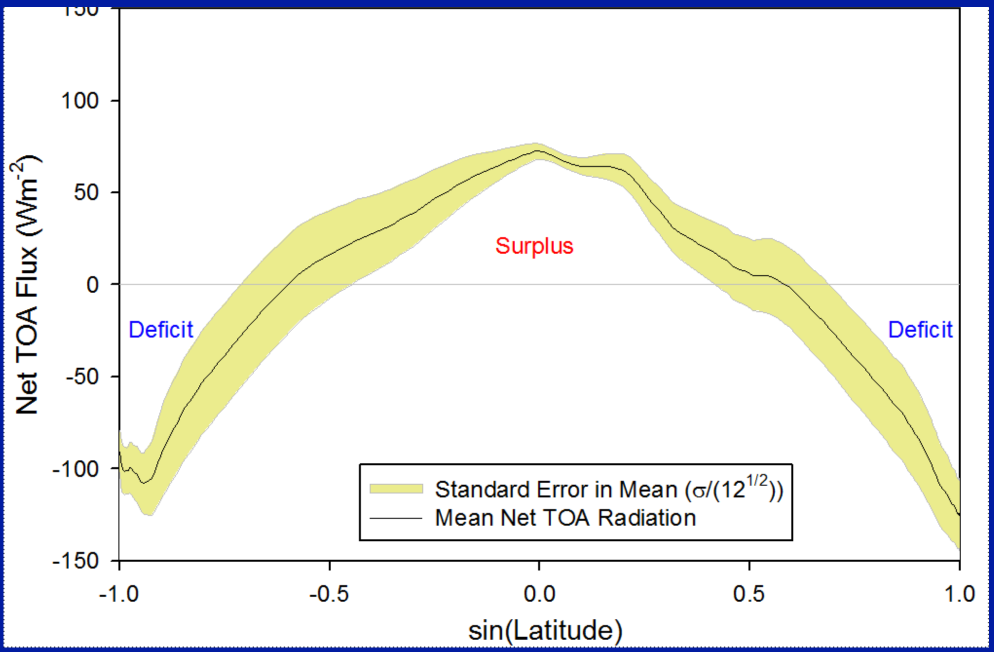
Earth's Energy Budget (Wm^{-2})

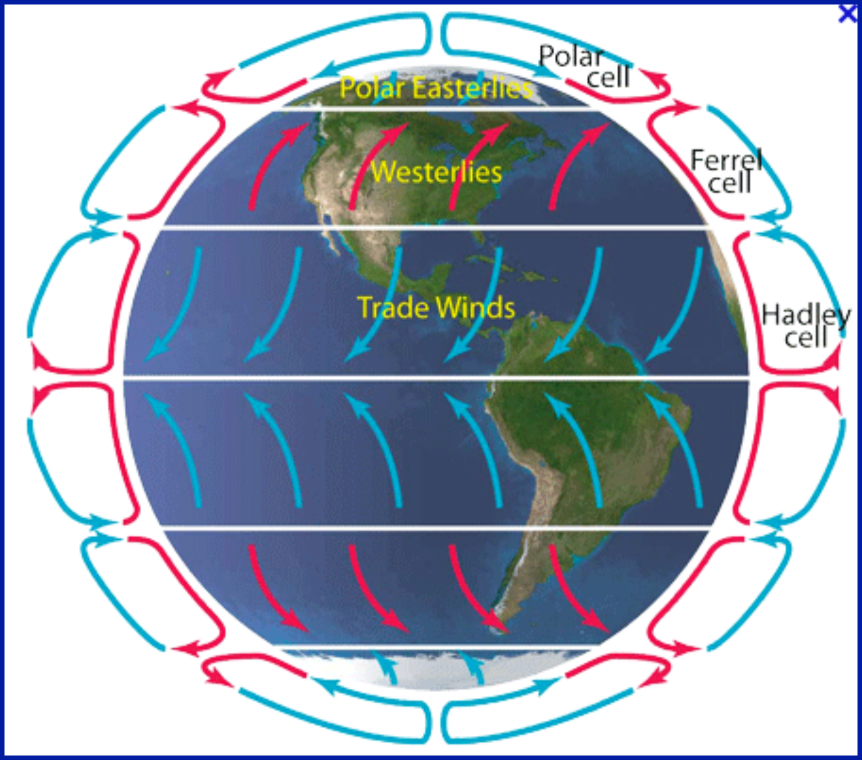


The radiative imbalance between the surface and atmosphere determines how much energy is available to drive the hydrological cycle and the exchange of sensible heat between the surface and atmosphere.

Why It's Important to Understand Earth's Radiation Budget

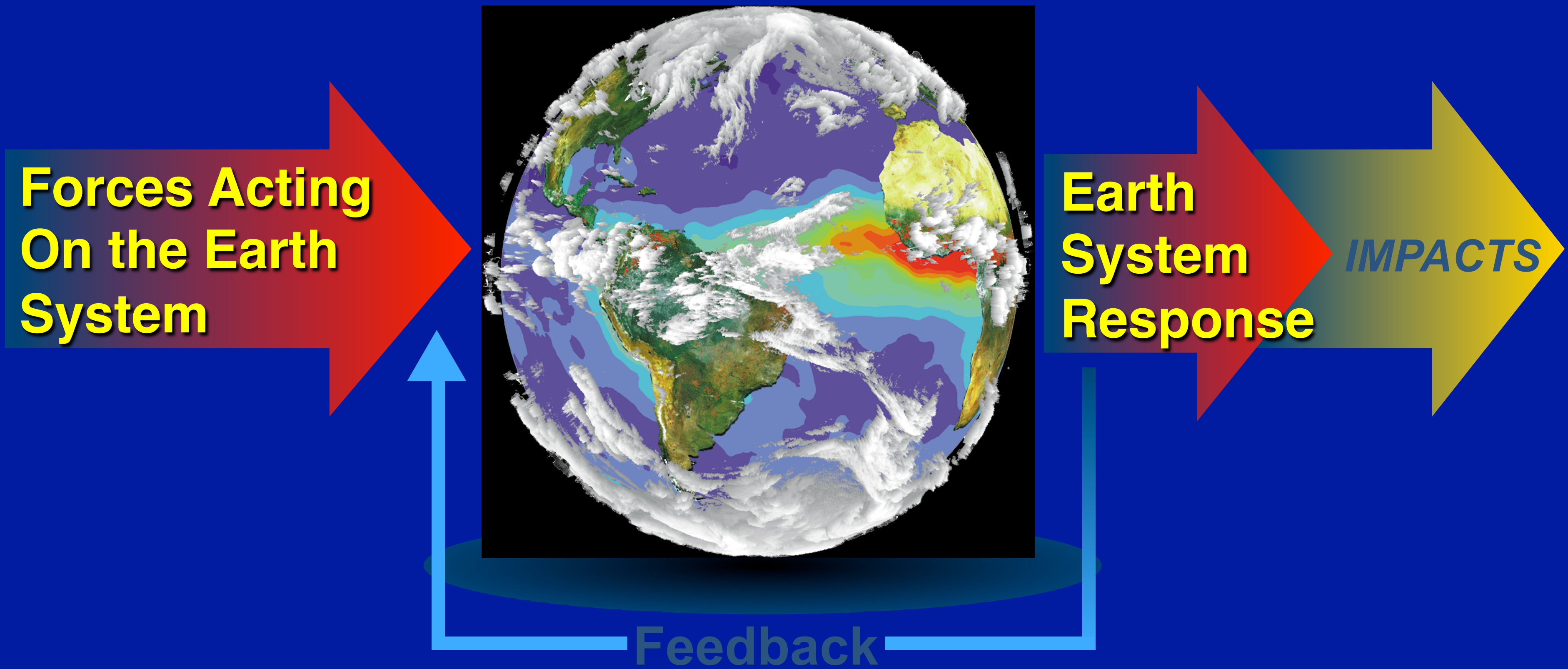
CERES Net TOA Radiation
(EBAF Ed2.6r Climatology: March 2000-June 2011)





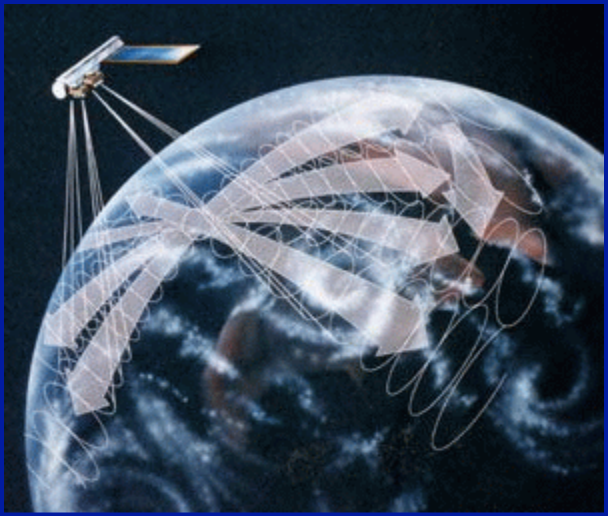
- Radiation imbalance between low and high latitudes is balanced by equator-to-pole heat transported by the atmosphere and oceans.
- The regional pattern of net radiation drives the atmospheric and oceanic circulations.

How does the Earth Respond?



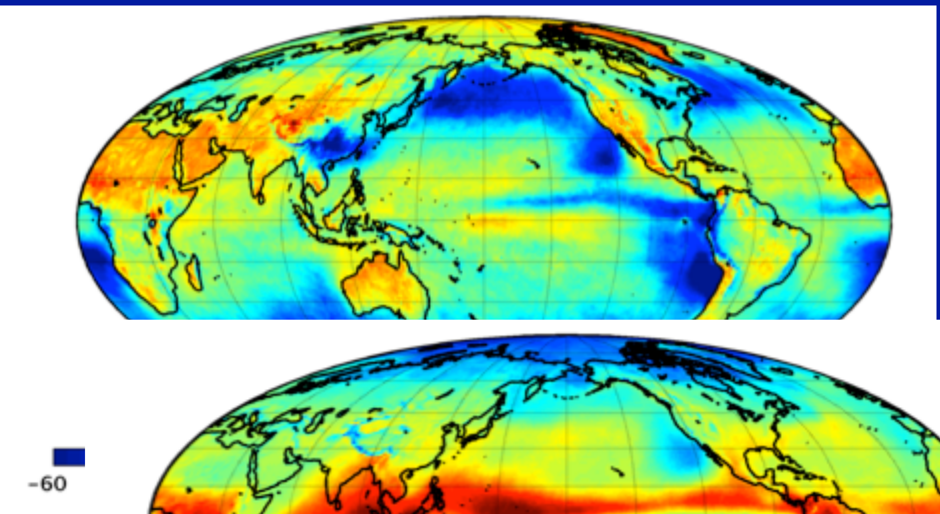
- Forcings include natural (sun, volcanic eruptions) and man-made (CO_2 and other GHGs, aerosols, land cover changes, etc.).
- Feedbacks include those due to water vapor, temperature/lapse rate, surface albedo, clouds.

Clouds and The Earth's Radiant Energy System



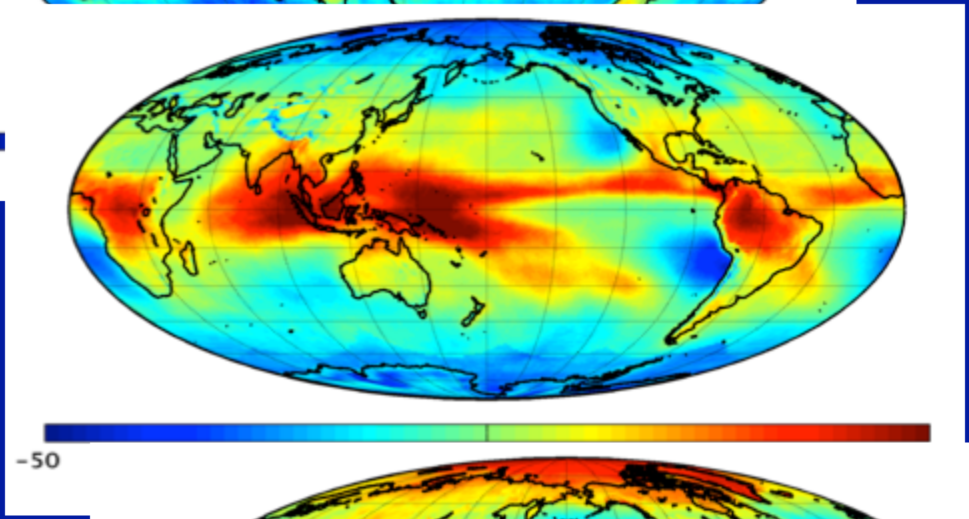
- Provide continuous long-term Earth radiation budget observations at the top-of-atmosphere, within-atmosphere and surface together with coincident cloud, aerosol and meteorological data.
- To enable improved understanding of the variability in Earth's radiation budget and the role clouds play.
- To provide data products for climate model evaluation and improvement.

CERES Data Fusion: Net Radiative Effects of Clouds on Earth's Radiation Budget



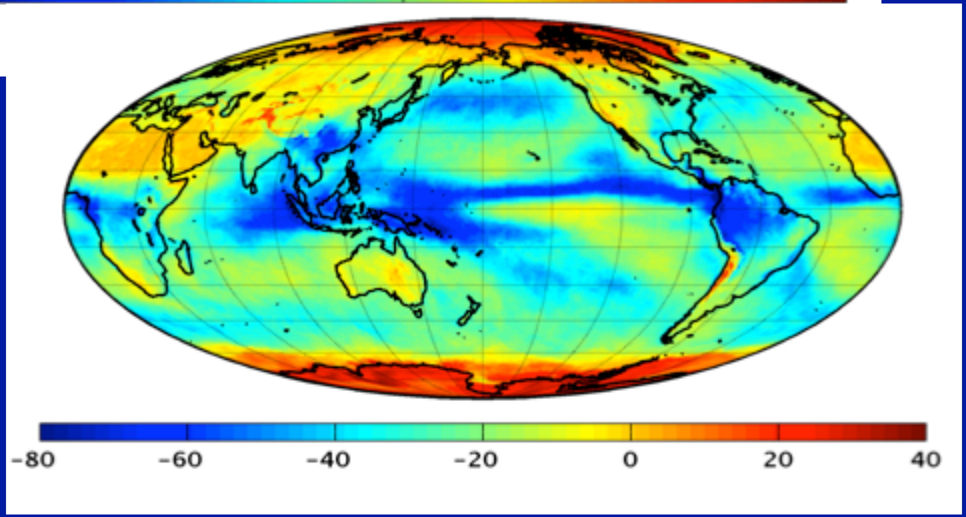
Top-of-Atmosphere (-20.9 Wm^{-2})

- SORCE-TIM: Solar Irradiance
- CERES: Reflected Solar, Emitted Thermal Flux
- MODIS: Cloud Detection & Properties
- 5 Geo Satellites: Diurnal Cycle



Within-Atmosphere (0.4 Wm^{-2})

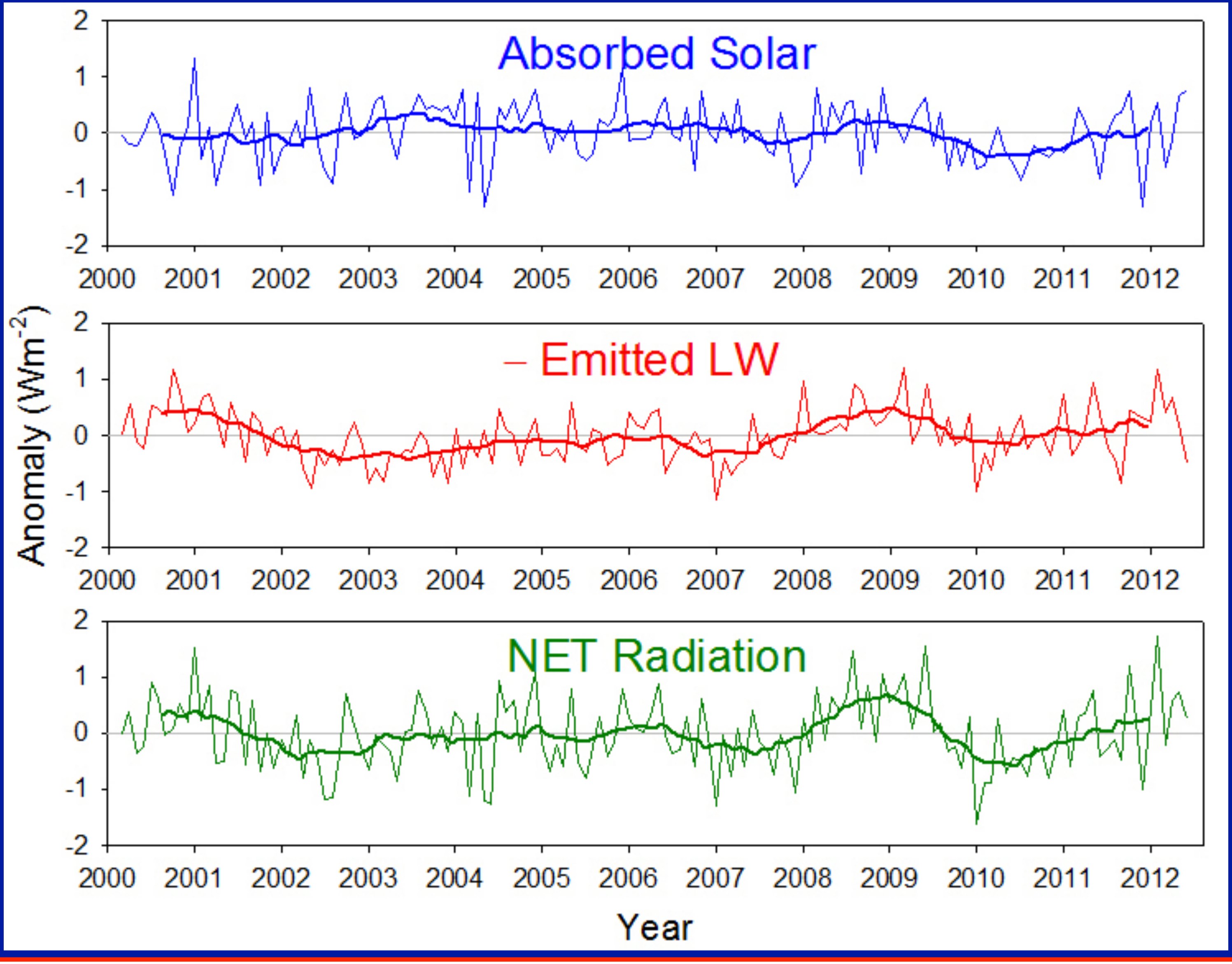
- MODIS: Aerosol & Cloud Properties
- GMAO Reanalysis: Atmospheric State
- Aerosol Assimilation
- Constraints from: AIRS, CALIPSO, CloudSat



Surface (-21.3 Wm^{-2})

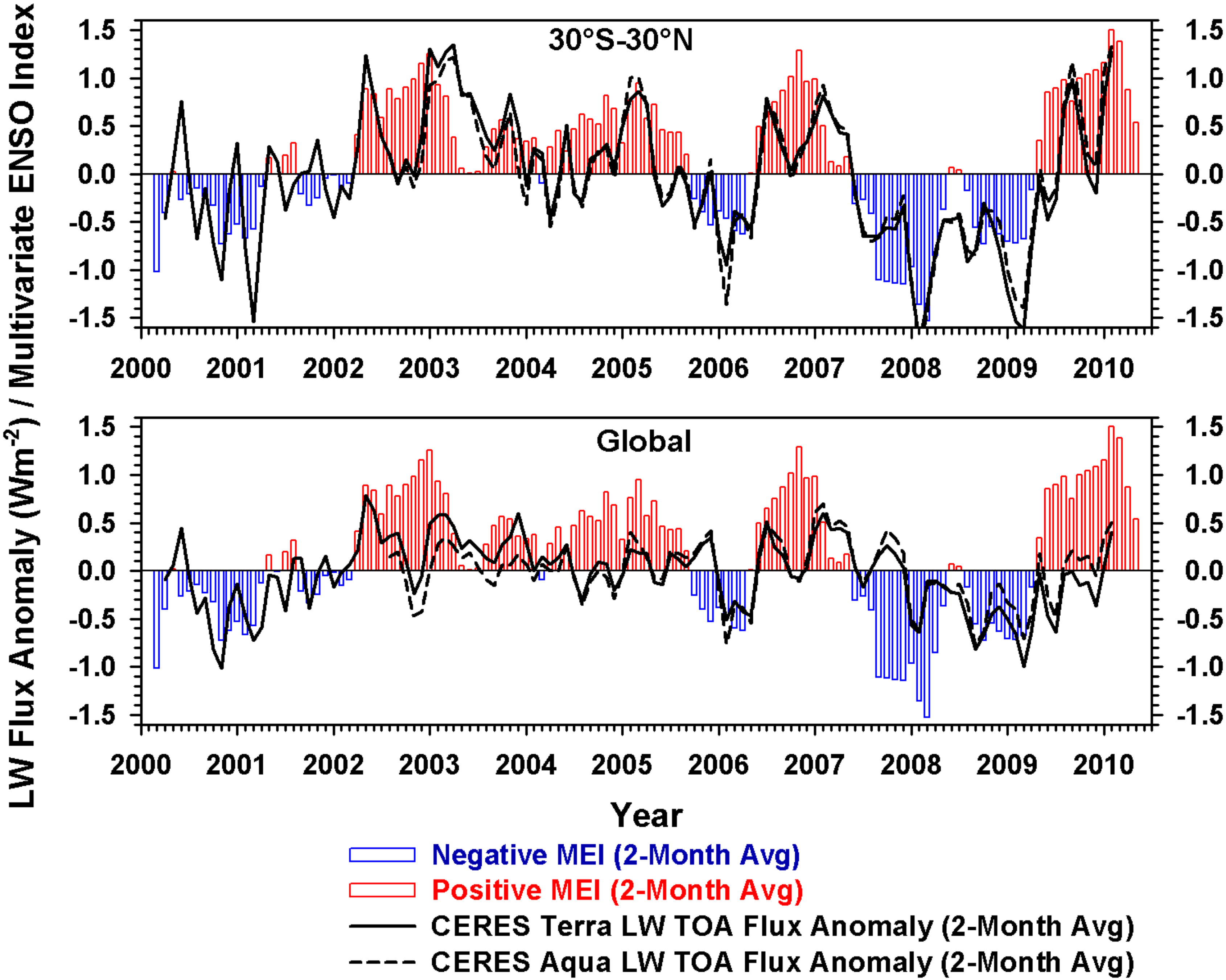
- MODIS: Surface albedo, emissivity & temperature
- NSIDC: Snow, sea-ice coverage

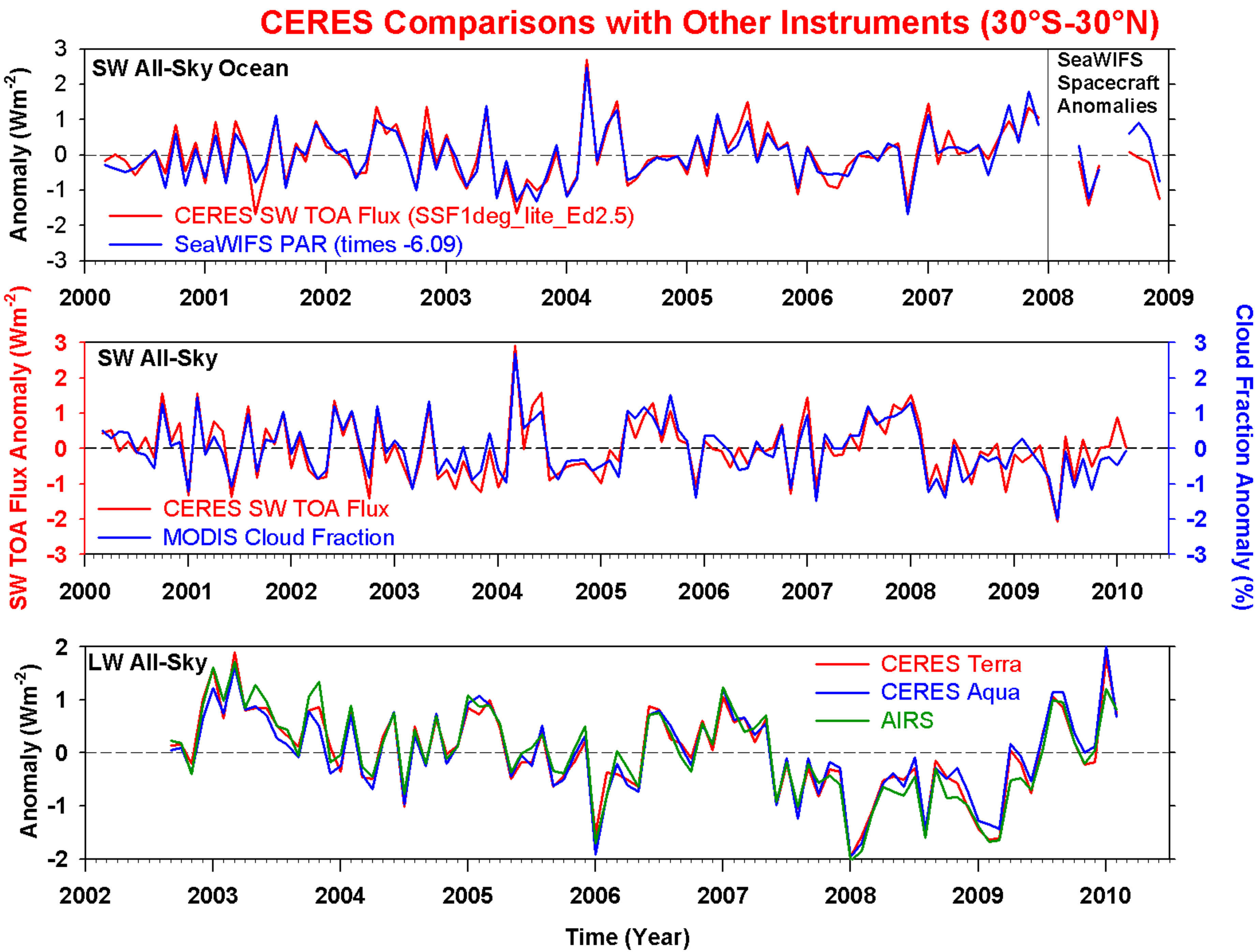
Global TOA **All-Sky** Radiation Anomalies
(CERES_EBAF_Ed2.6r; 03/2000 – 06/2012))



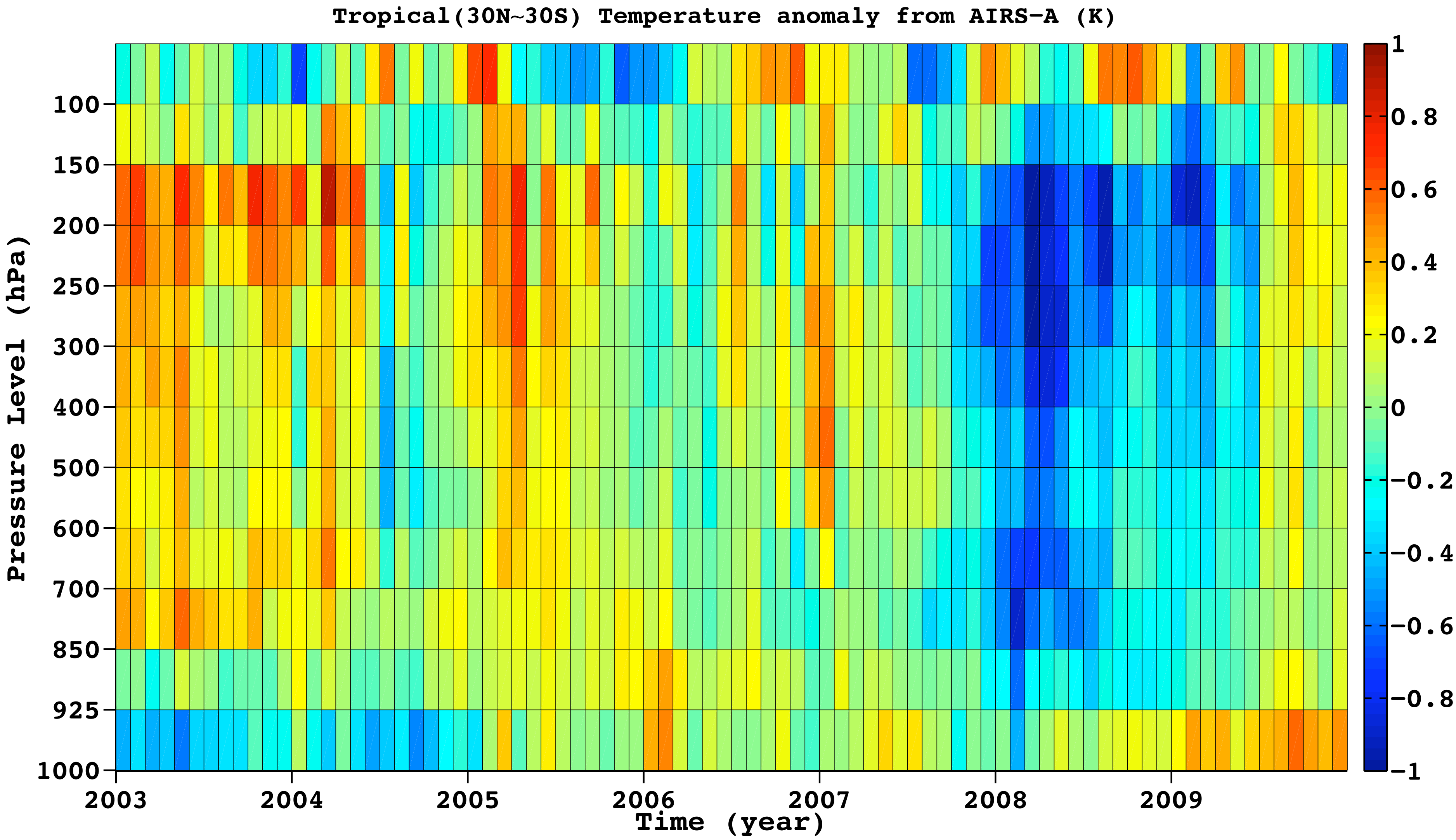
Earth has steadily been accumulating energy at the rate 0.5 ± 0.43 Wm^{-2} (90% conf) during the past decade.

Outgoing LW Radiation Anomalies (CERES) and ENSO Index




CERES Comparisons with Other Instruments (30°S-30°N)
SW All-Sky Ocean
SeaWIFS Spacecraft Anomalies
CERES SW TOA Flux (SSF1deg_lite_Ed2.5)
SeaWIFS PAR (times -6.09)
Anomaly (Wm-2)
SW All-Sky
CERES SW TOA Flux
MODIS Cloud Fraction
SW TOA Flux Anomaly (Wm-2)
Cloud Fraction Anomaly (%)
LW All-Sky
CERES Terra
CERES Aqua
AIRS
Anomaly (Wm-2)
Time (Year)

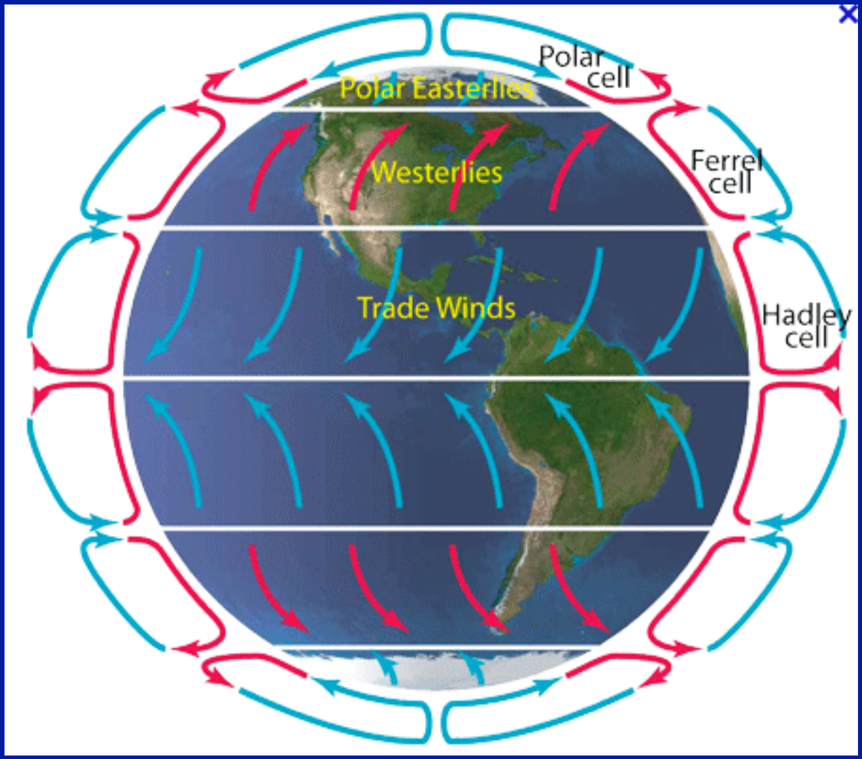
AIRS Temperature Anomaly (30°S-30°N)

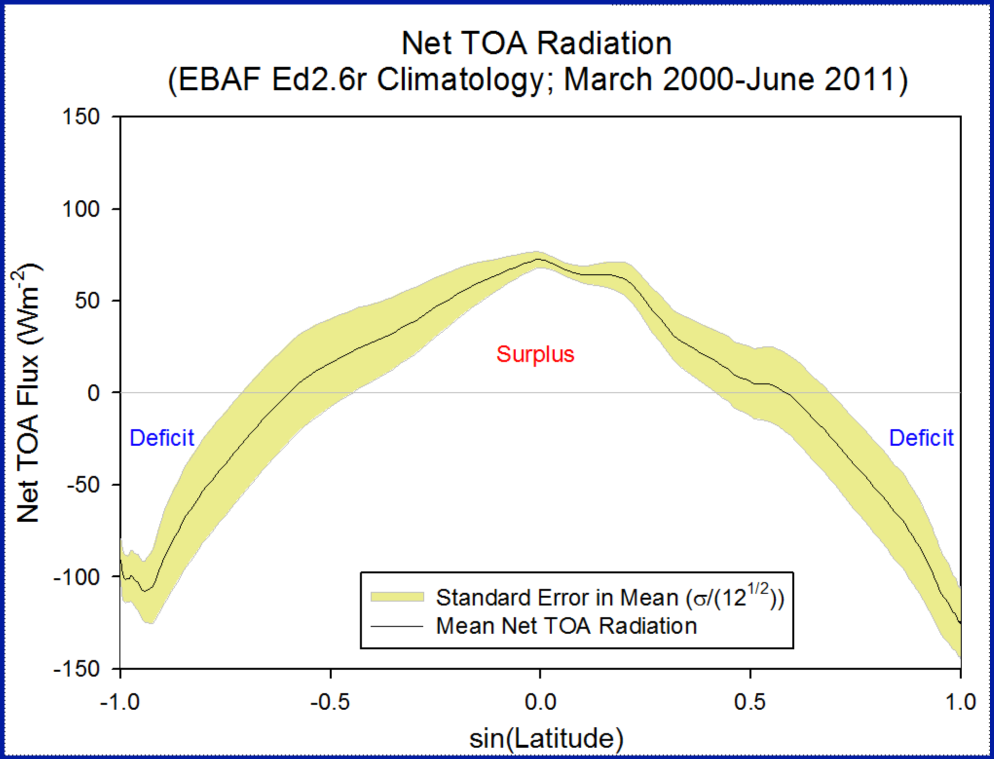


Co-Variability of Clouds, Radiation & Large-Scale Atmospheric Circulation

Hadley Circulation

- Zonally symmetric meridional circulation with ascending motion over ITCZ and descending motion over subtropical high pressure belt.
- Driven by meridional differential radiative heating. Expected to weaken and expand under global warming.
- How do clouds and radiation co-vary with Hadley circulation strength?
- Do climate models reproduce observed behavior?





Hadley Cell Strength and Stream Function Gradient

- Strength of the mean meridional overturning of mass for 0-30°N for northern branch and 0-30°S for southern branch.
- Determine Stokes stream function (Ψ) from zonal mean meridional velocity (Oort and Yienger, 1996):

$$\Psi = \frac{2\pi R \cos\theta}{g} \int_0^p \bar{v}\,dp$$

$\bar{v}$ = zonal mean meridional velocity
p=pressure
R=Radius of Earth
θ=Latitude
g=Acceleration due to gravity

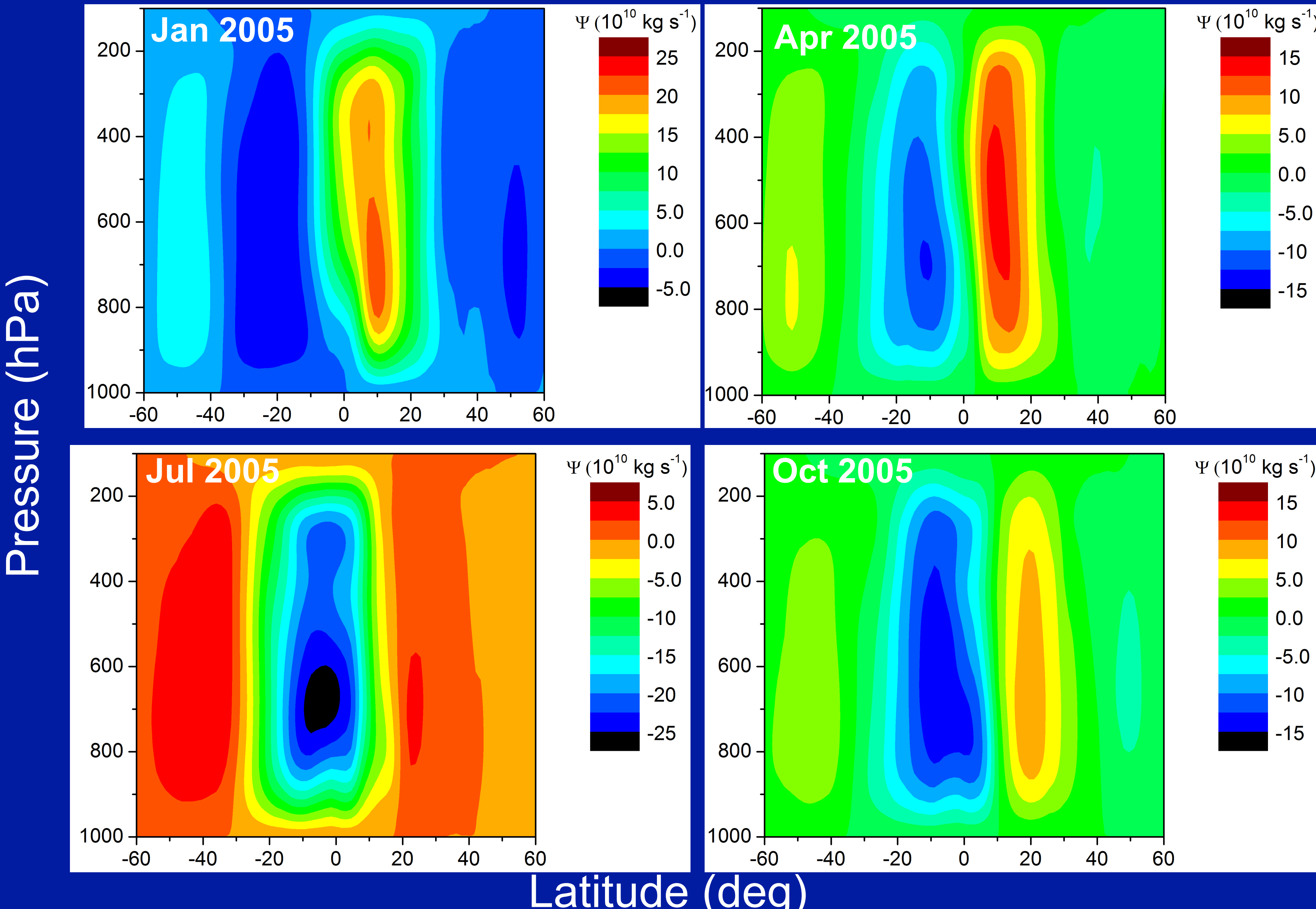
- Strength of NH and SH branches of Hadley Cell:
  Ψ_{max} for 0-30°N
  Ψ_{min} for 0-30°S

- Vertical velocity proportional to latitudinal gradient in stream function :

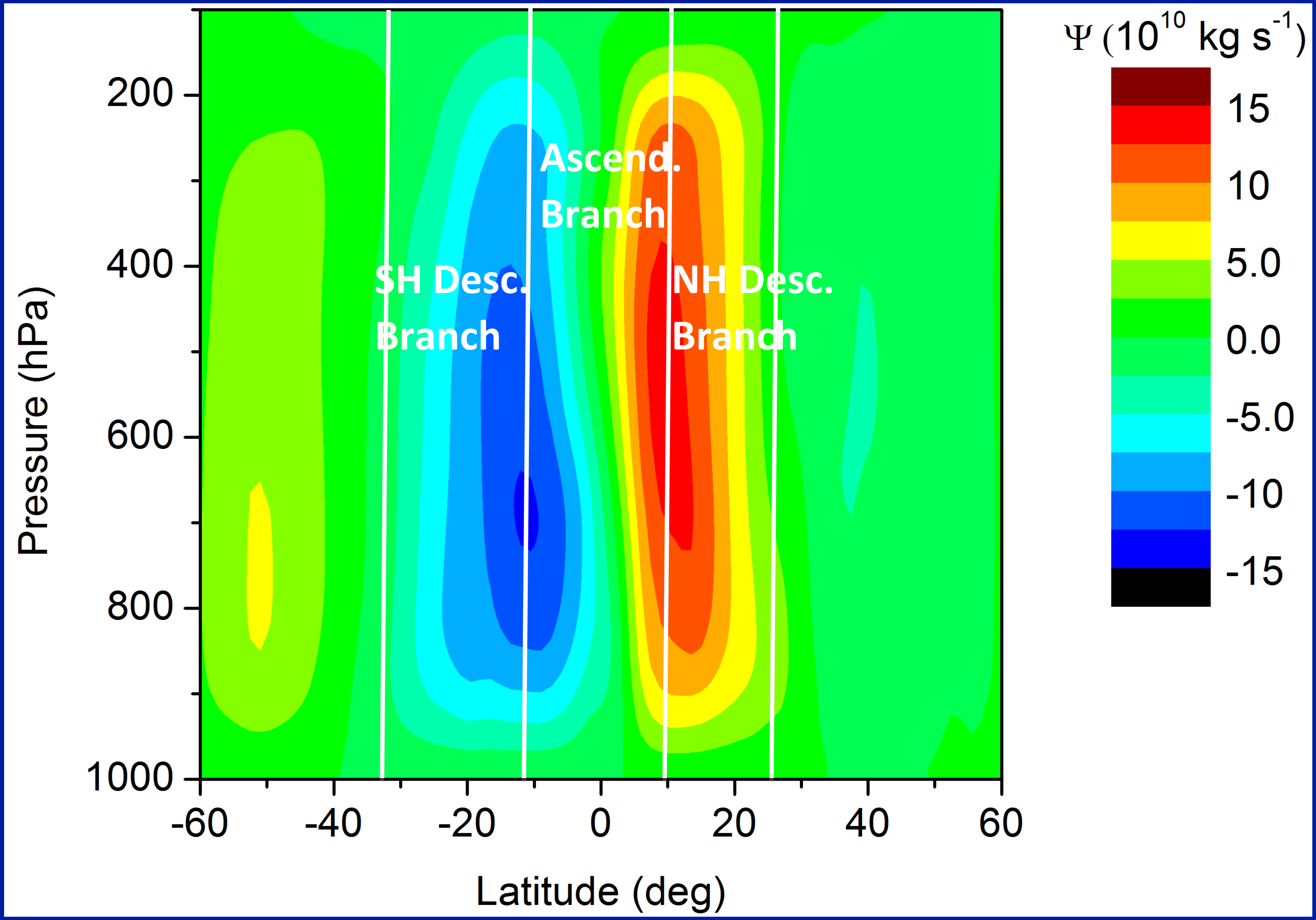
$$\bar{\omega} = -\frac{g}{2\pi R^2 \cos\theta}\left(\frac{\partial \Psi}{\partial \theta}\right)$$

- This study uses ERA-Interim monthly mean meridional velocity

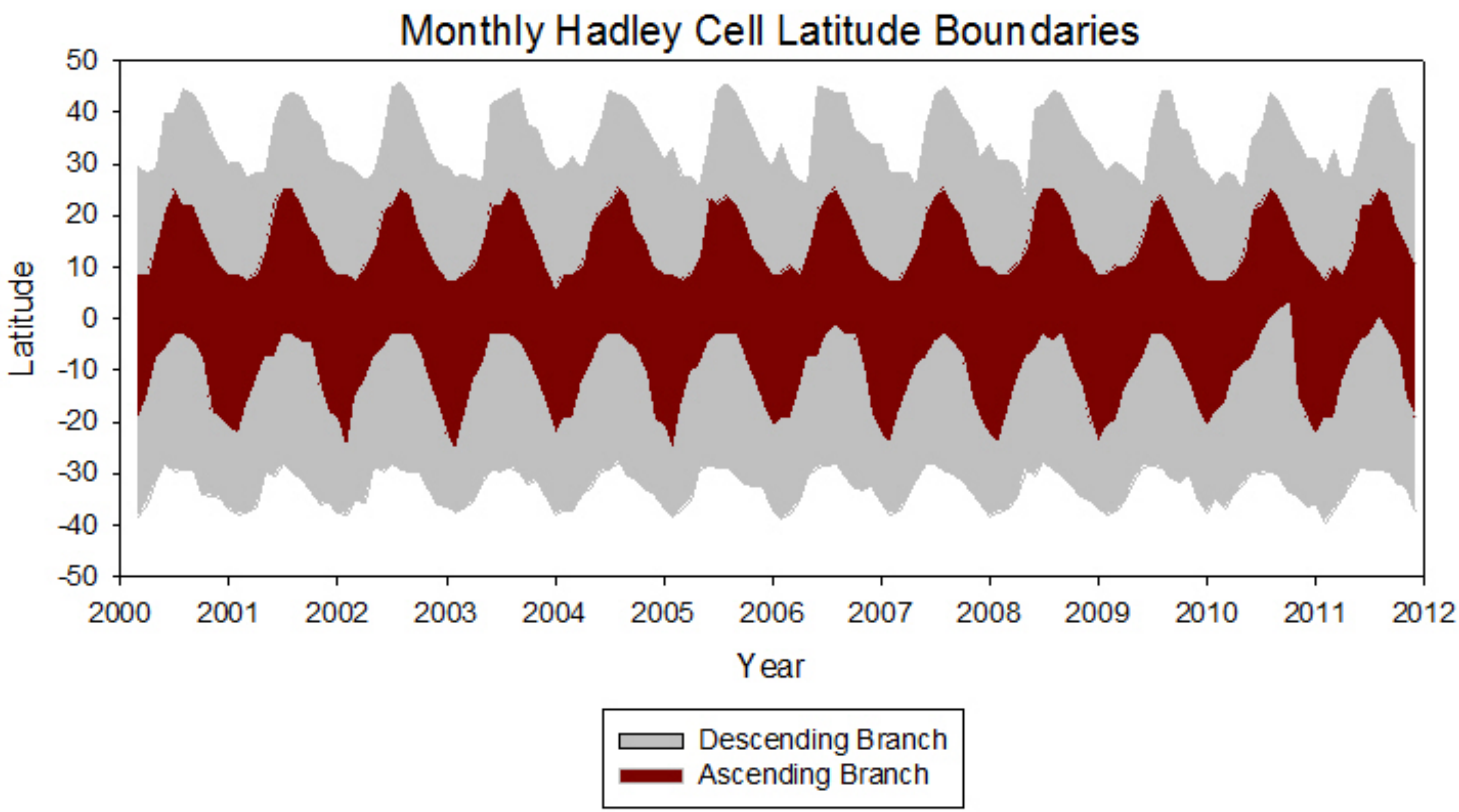
Zonal Mean Mass Streamfunction (Ψ) by Season



Analysis Domains: 3 Branches of Hadley Ciculation

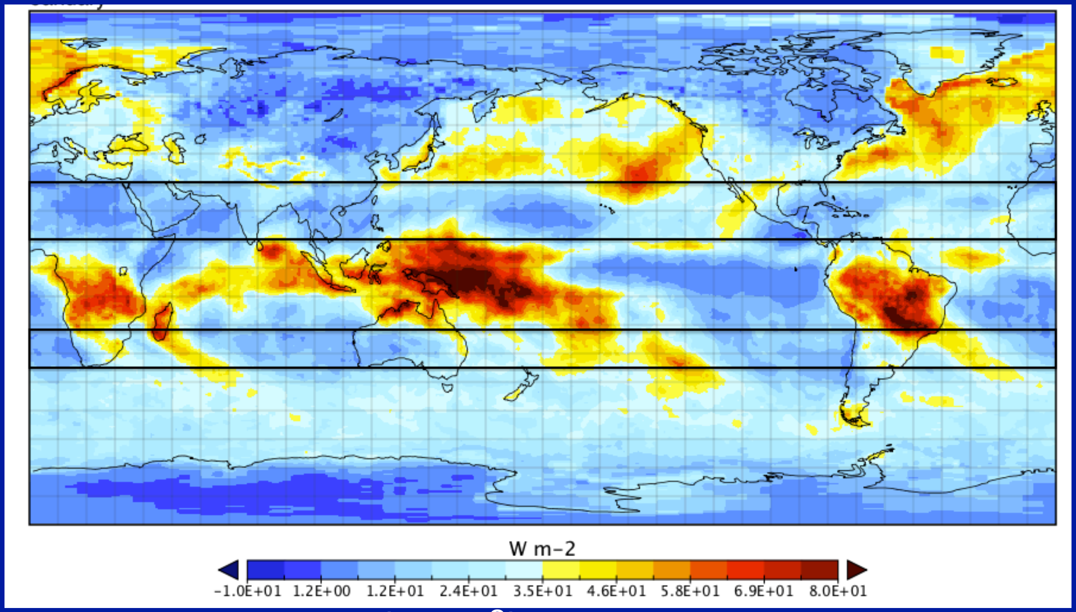


- Stratify CERES observations according to location of 3 branches of Hadley Circulation.
- The averaging domains change with season (follow large-scale circulation).

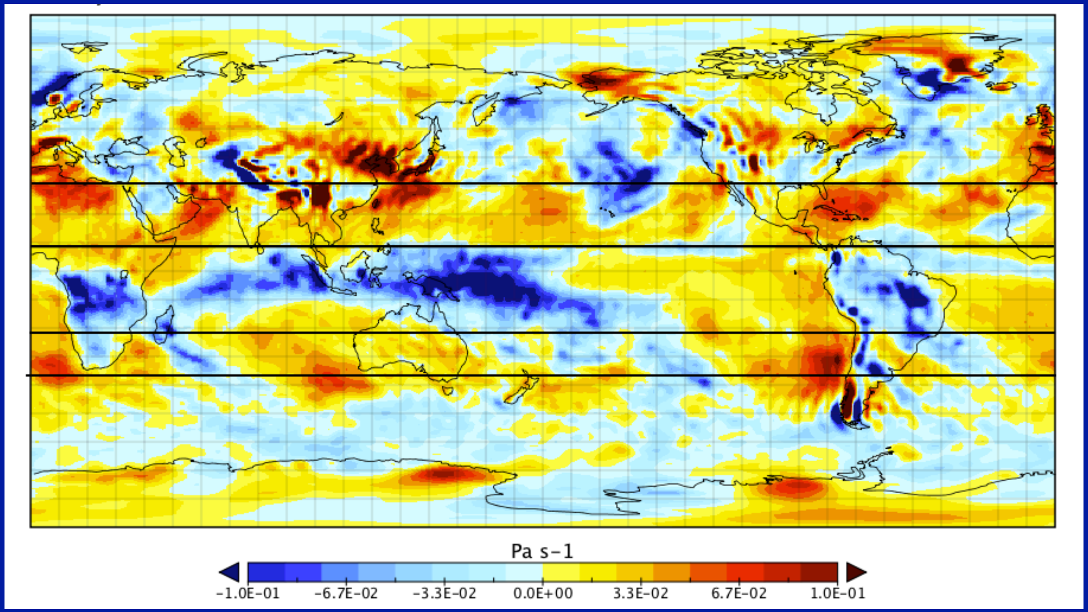


Monthly Hadley Cell Latitude Boundaries
Latitude
50
40
30
20
10
0
-10
-20
-30
-40
-50
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
Year
Descending Branch
Ascending Branch

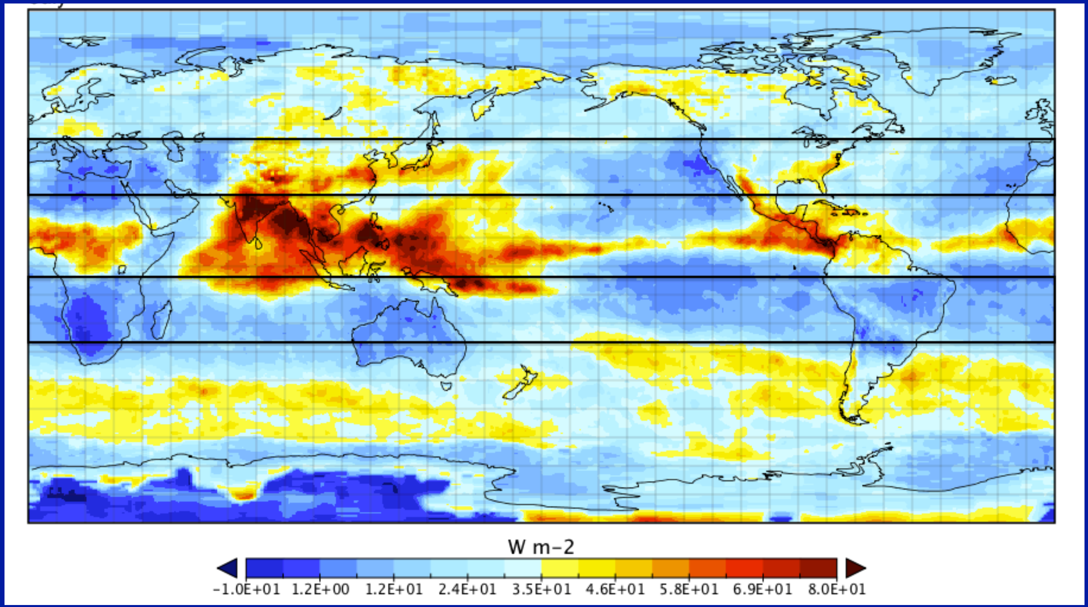
TOA LW Cloud Radiative Effect (Wm^{-2}) January 2005



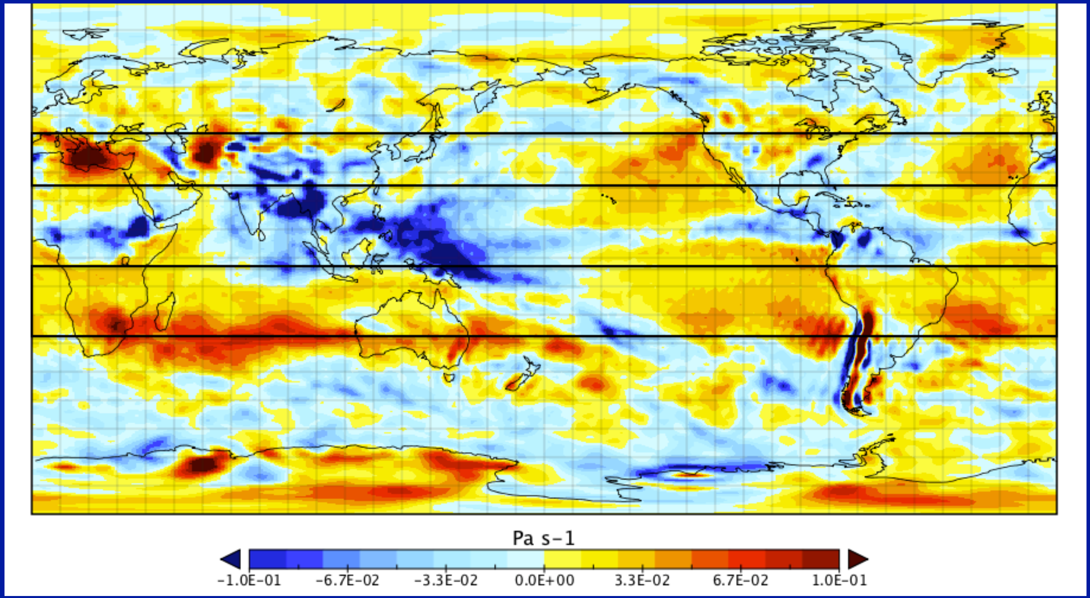
ω_{500} (Wm^{-2}) January 2005



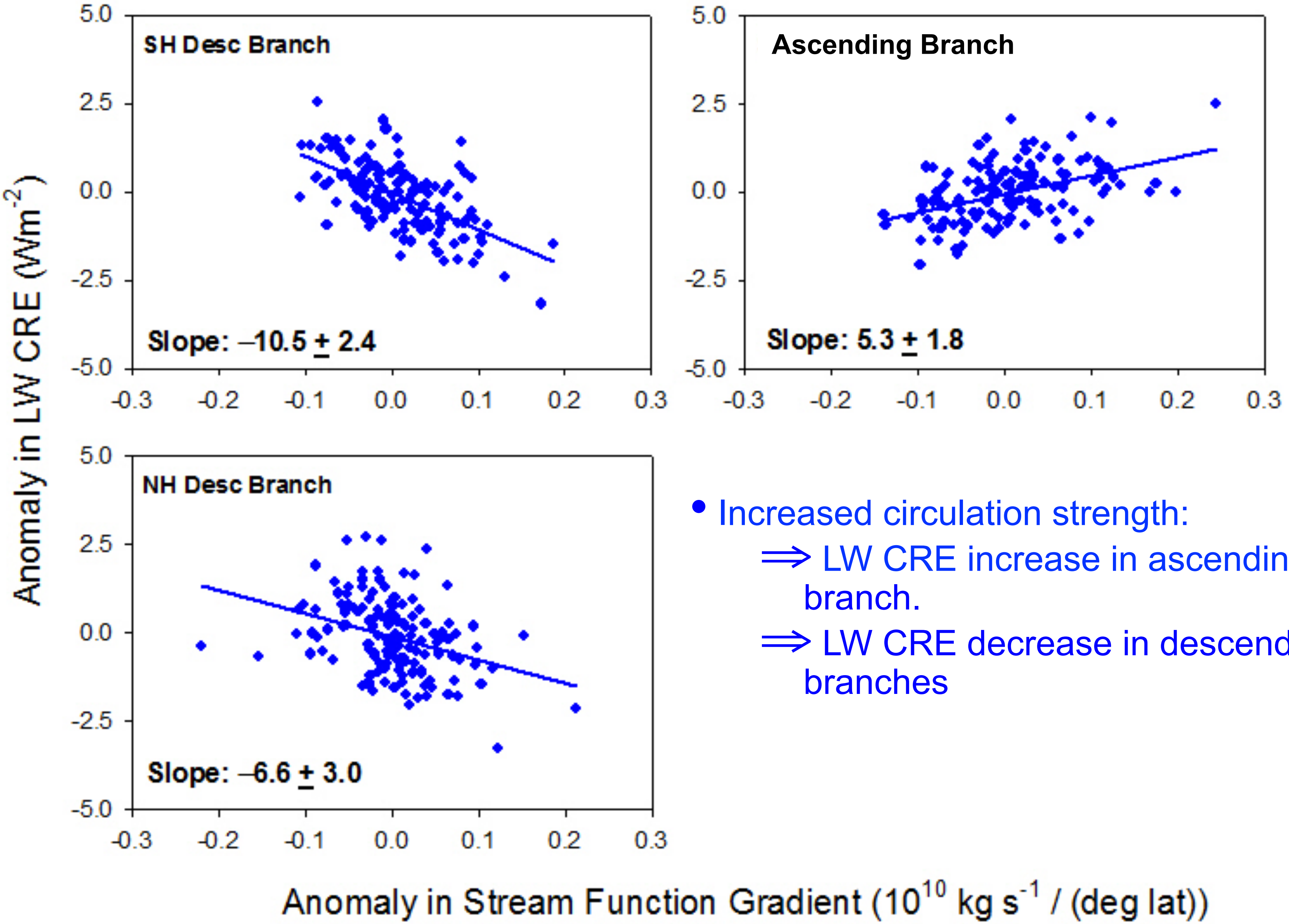
TOA LW Cloud Radiative Effect (Wm^{-2}) July 2005



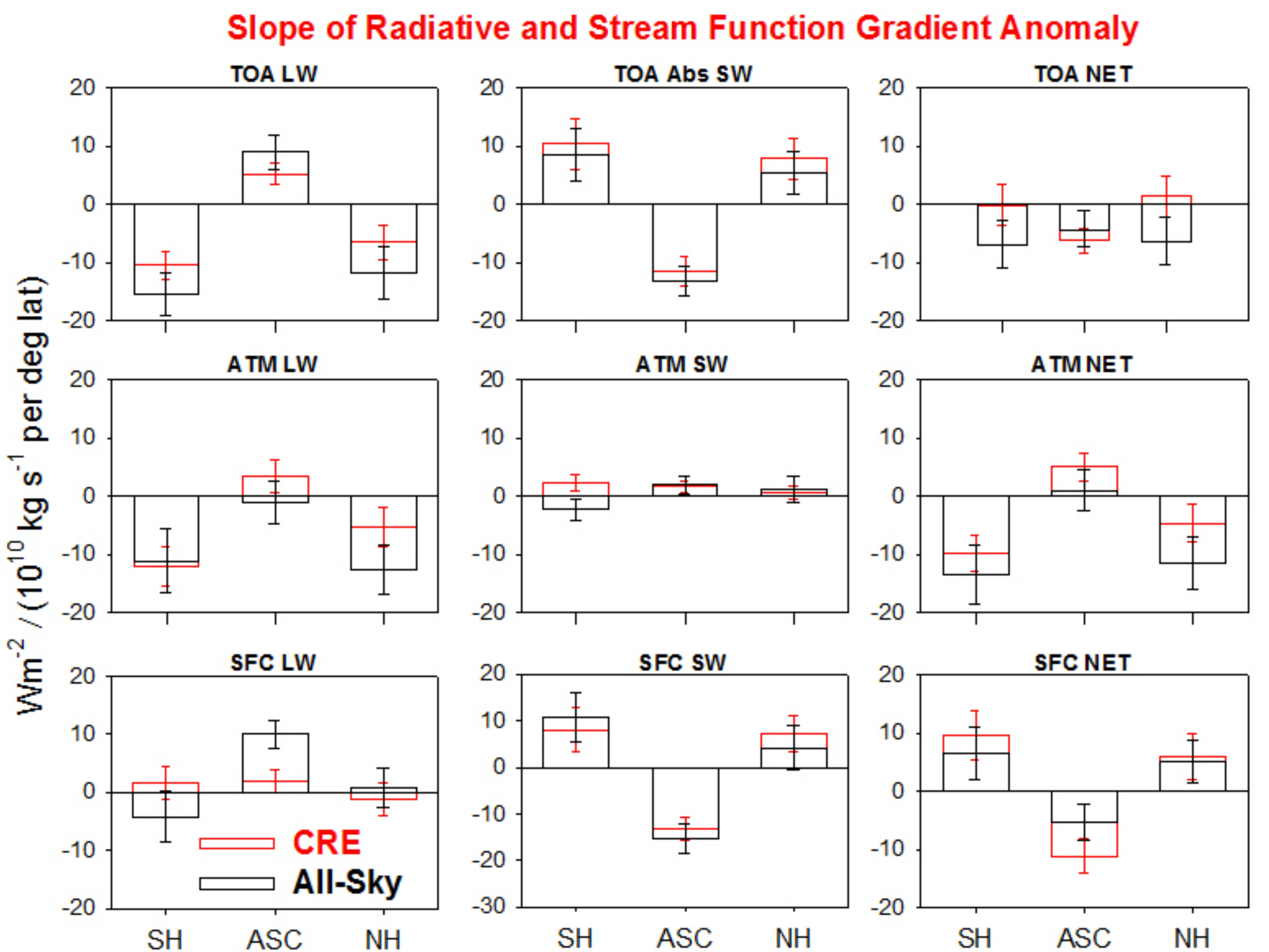
ω_{500} (Wm^{-2}) July 2005



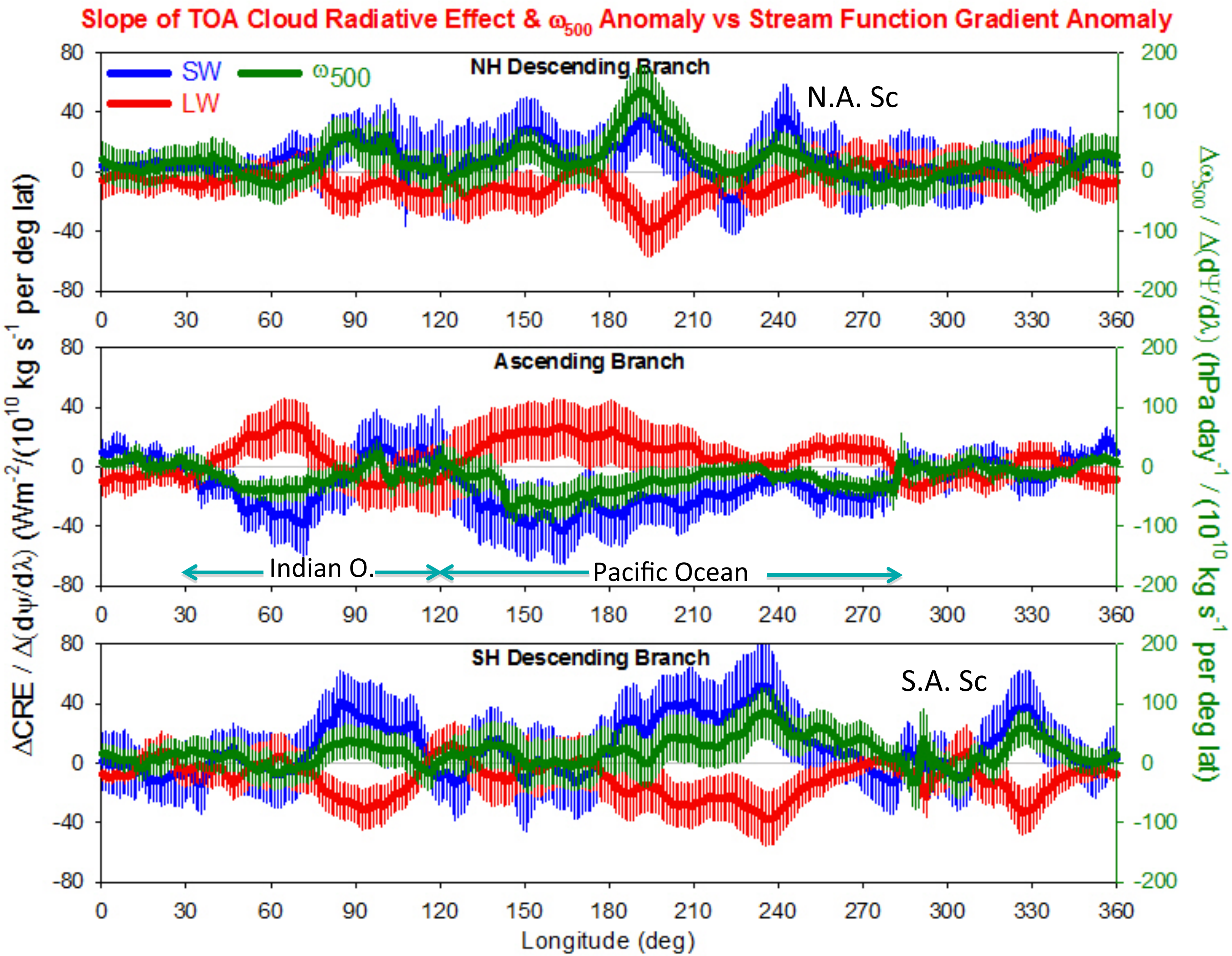
CERES TOA LW CRE Anomaly vs Stream Function Gradient Anomaly



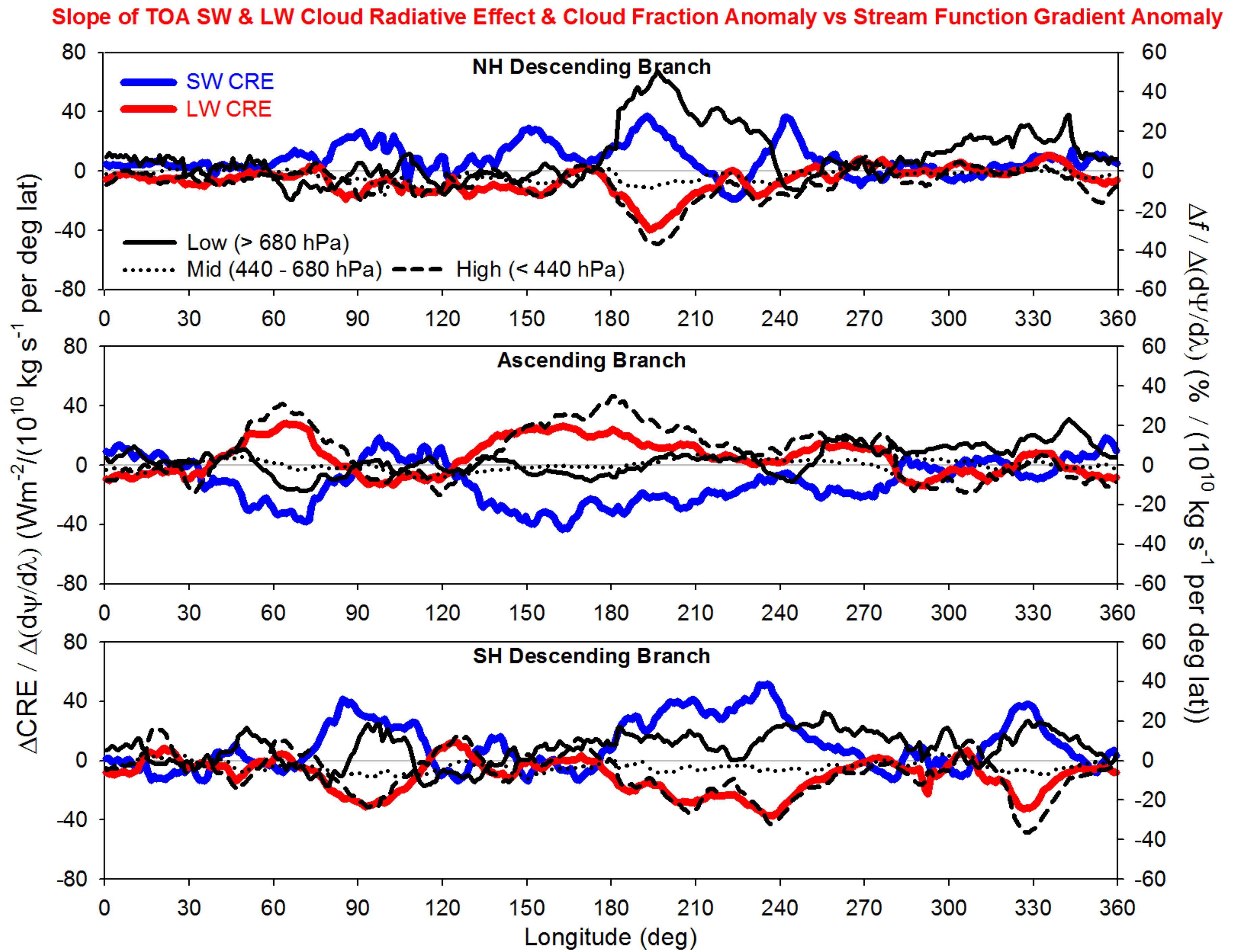
- Increased circulation strength:
  - ⟹ LW CRE increase in ascending branch.
  - ⟹ LW CRE decrease in descending branches



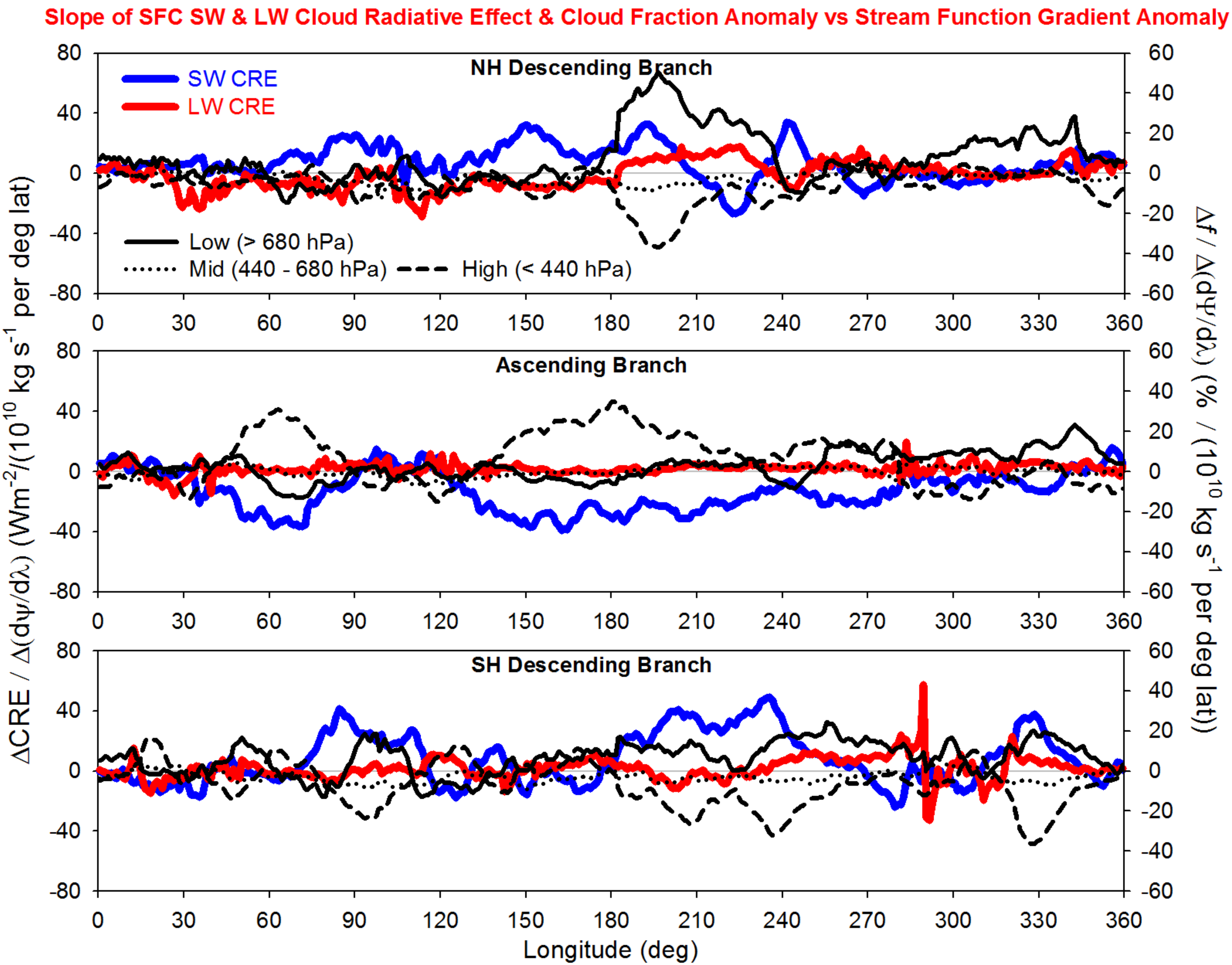
Slope of Radiative and Stream Function Gradient Anomaly
TOA LW
TOA Abs SW
TOA NET
ATM LW
ATM SW
ATM NET
SFC LW
SFC SW
SFC NET
Wm^{-2} / (10^{10} kg s^{-1} per deg lat)
CRE
All-Sky
SH
ASC
NH



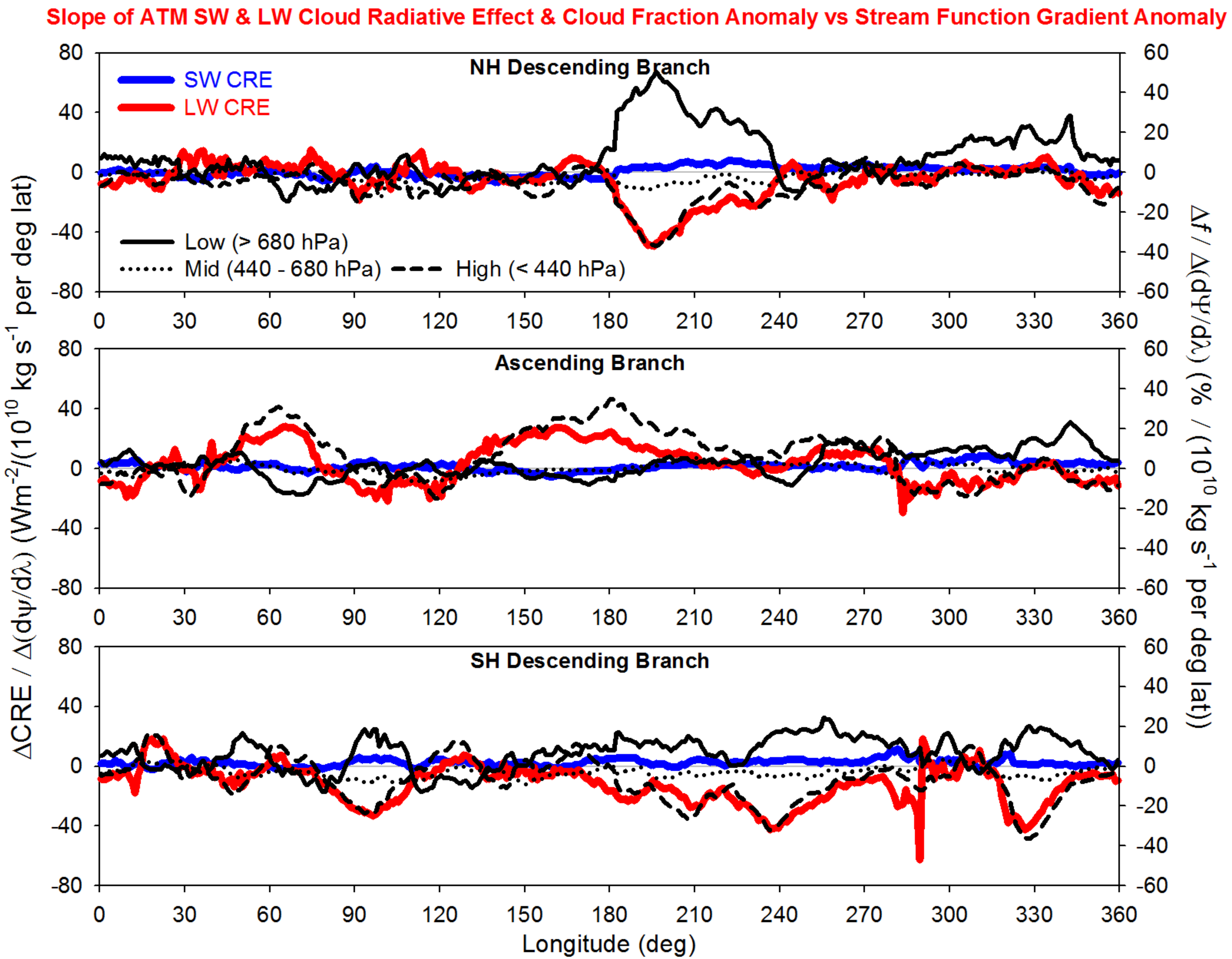
Slope of TOA Cloud Radiative Effect & ω_{500} Anomaly vs Stream Function Gradient Anomaly
SW
LW
ω_{500}
NH Descending Branch
N.A. Sc
Ascending Branch
Indian O.
Pacific Ocean
SH Descending Branch
S.A. Sc
$\Delta CRE / \Delta(d\psi/d\lambda)$ ($Wm^{-2}/(10^{10}$ kg s^{-1} per deg lat)
$\Delta\omega_{500} / \Delta(d\Psi/d\lambda)$ (hPa day^{-1} / (10^{10} kg s^{-1} per deg lat)
Longitude (deg)



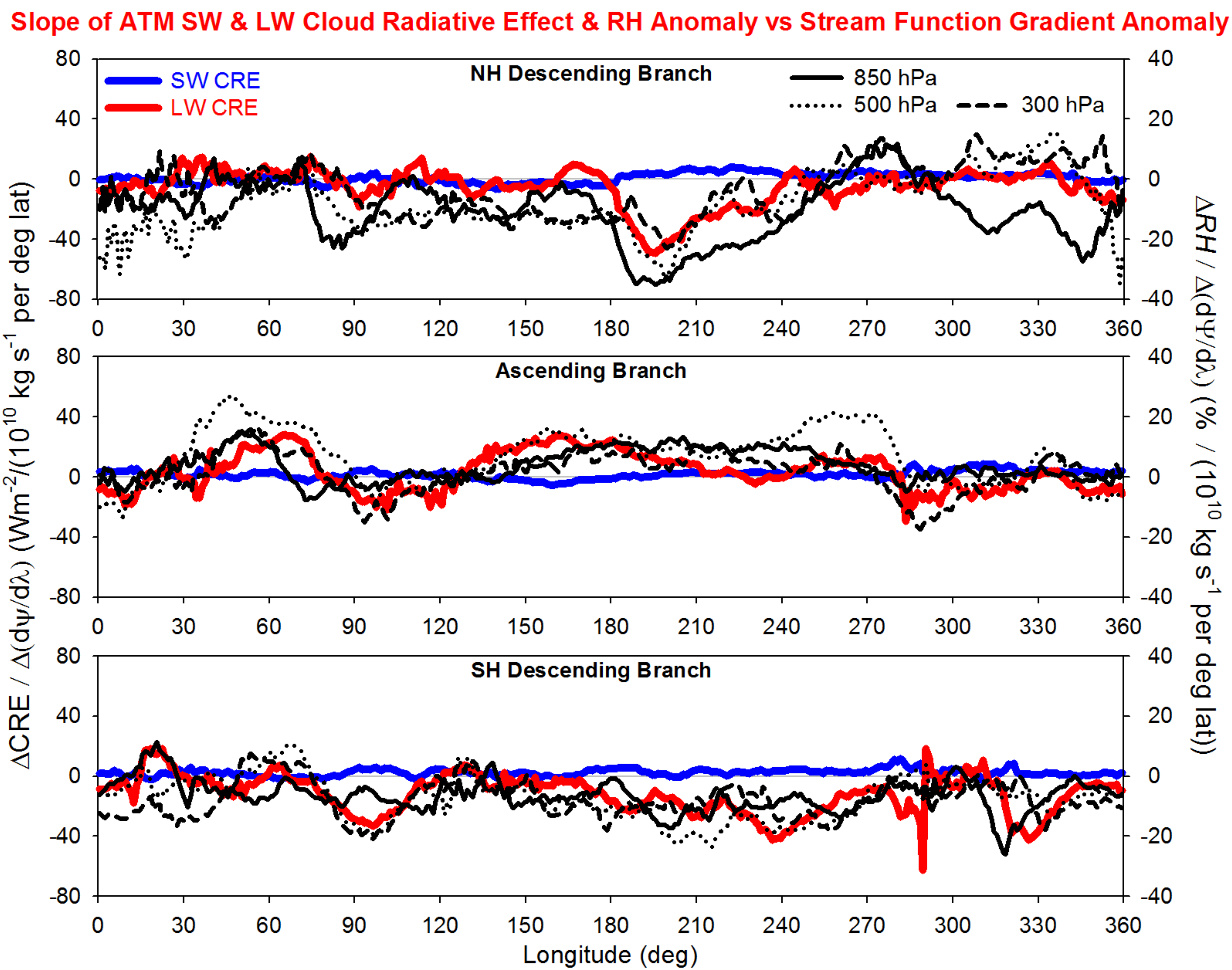
Slope of TOA SW & LW Cloud Radiative Effect & Cloud Fraction Anomaly vs Stream Function Gradient Anomaly
NH Descending Branch
SW CRE
LW CRE
Low (> 680 hPa)
Mid (440 - 680 hPa)
High (< 440 hPa)
Ascending Branch
SH Descending Branch
ΔCRE / Δ(dψ/dλ) (Wm⁻²/(10¹⁰ kg s⁻¹ per deg lat)
Δf / Δ(dΨ/dλ) (% / (10¹⁰ kg s⁻¹ per deg lat))
Longitude (deg)



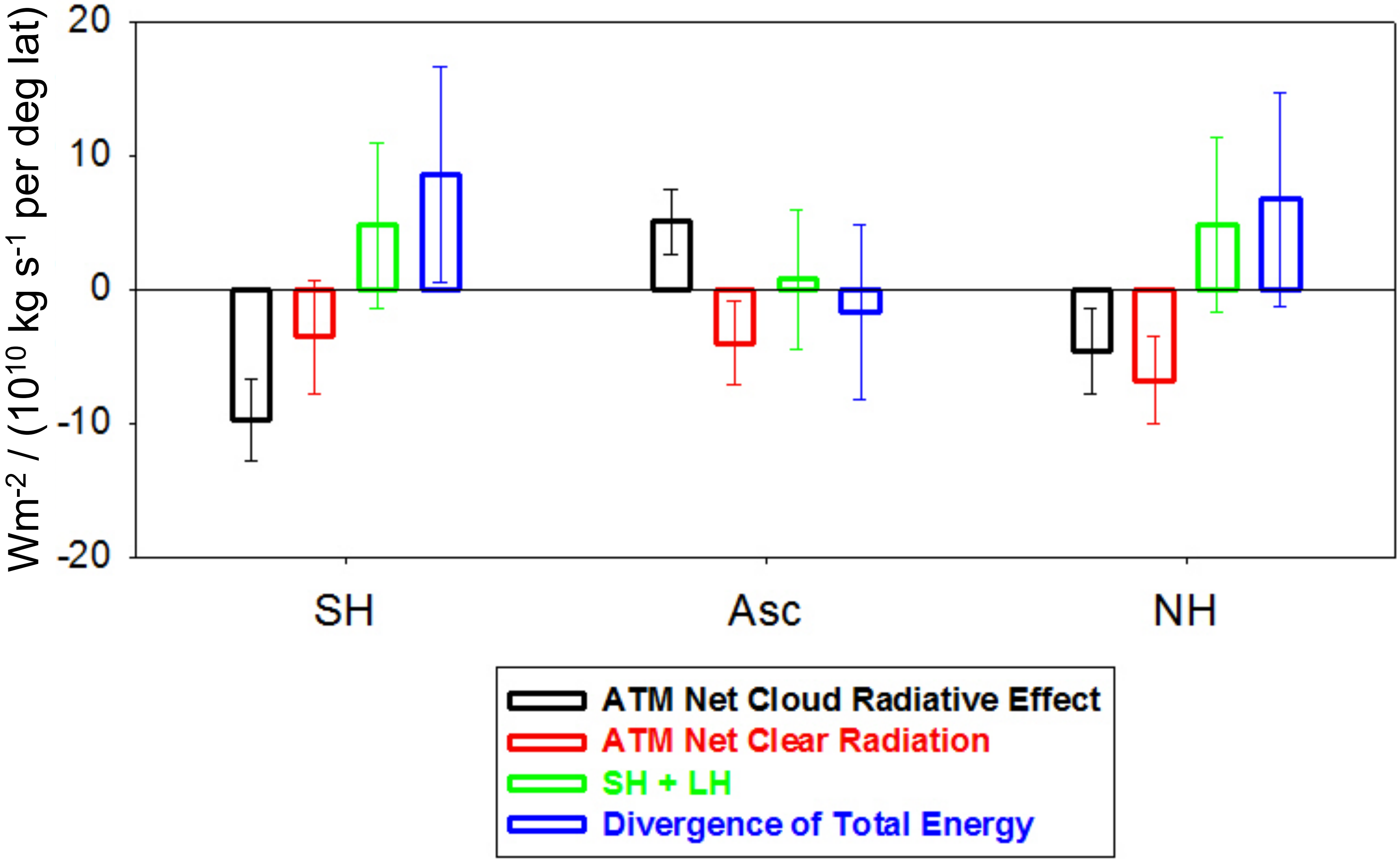
Slope of SFC SW & LW Cloud Radiative Effect & Cloud Fraction Anomaly vs Stream Function Gradient Anomaly
NH Descending Branch
SW CRE
LW CRE
Low (> 680 hPa)
Mid (440 - 680 hPa)
High (< 440 hPa)
Ascending Branch
SH Descending Branch
ΔCRE / Δ(dψ/dλ) (Wm⁻²/(10¹⁰ kg s⁻¹ per deg lat)
Δf / Δ(dΨ/dλ) (% / (10¹⁰ kg s⁻¹ per deg lat))
Longitude (deg)



Slope of ATM SW & LW Cloud Radiative Effect & Cloud Fraction Anomaly vs Stream Function Gradient Anomaly
NH Descending Branch
SW CRE
LW CRE
Low (> 680 hPa)
Mid (440 - 680 hPa)
High (< 440 hPa)
Ascending Branch
SH Descending Branch
ΔCRE / Δ(dψ/dλ) (Wm⁻²/(10¹⁰ kg s⁻¹ per deg lat)
Δf / Δ(dΨ/dλ) (% / (10¹⁰ kg s⁻¹ per deg lat))
Longitude (deg)


Slope of ATM SW & LW Cloud Radiative Effect & RH Anomaly vs Stream Function Gradient Anomaly
SW CRE
LW CRE
NH Descending Branch
850 hPa
500 hPa
300 hPa
Ascending Branch
SH Descending Branch
ΔCRE / Δ(dψ/dλ) (Wm⁻²/(10¹⁰ kg s⁻¹ per deg lat)
ΔRH / Δ(dΨ/dλ) (% / (10¹⁰ kg s⁻¹ per deg lat))
Longitude (deg)

Within-Atmosphere Sensitivity to Variations in Stream Function Gradient



- ATM fluxes inferred from CERES EBAF (TOA & SFC)
- SH + LH determined from WHOI OAFlux product (ocean only)
- Divergence of total energy computed as residual: $R_{CLR} + CRE + SH + LH - Div\_E_T = 0$

Conclusions

- Current observations (e.g., A-Train) provide unprecedented detail on how clouds, radiation and atmospheric state co-vary in response to natural fluctuations in the climate system (e.g., ENSO, NAO, etc.).

In response to intensification in Hadley circulation:

- Magnitudes of SW & LW cloud radiative effects at TOA & SFC increase in ascending branch of Hadley circulation. Opposite is true in descending branches.
- Net effect on radiation in ATM is cooling in descending branches. Small radiative impact in ascending branch due to opposing changes in clear and cloudy regions.
- Changes in high cloud amount explain most of the longitudinal variability in radiation associated with changes in circulation strength.
- SH+LH and divergence of total energy compensate for radiative cooling in descending branches.
- Do climate models reproduce observed relationships?

End